Physics of Neutron Stars 2

Evolution of Neutron Stars

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Outline

Introduction

Neutron Star cooling

Cooling and Pairing

Cooling and EoS

A bit about Observations

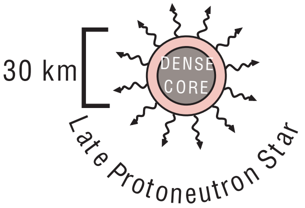
Neutron Star Structure

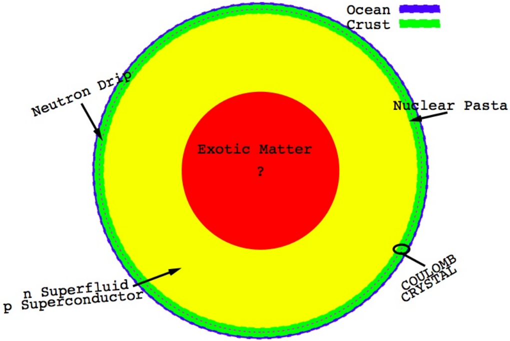
Next

Previously ...

- Simplified Stellar Model
- Stellar Evolution: from heavy stars ($\mathcal{M} > 8\mathcal{M}_\odot$) to compact objects.
- Supernovae type IIa: Gravitational Collapse. 99% of the energy is released in νs.
- νs from the core (assisted by other mechanisms) resuscitate the shock (no conclusive),
  $\Rightarrow$ expelling the massive stellar mantle
  See paper by Hammer, Janka, and Müller, ApJ **714 1371((2010)** .
- The ejected material by supernovae contains heavy elements.
- Proto-neutron star shrinks because of the losses of neutrinos.
- Left is a proto-neutron star.

Supernovae Remnant ⇒ Neutron Star





Neutron Star cooling

Weeks after the explosion, $T \sim 10^9 - 10^{10}$ K.

$$C_V(T_i)\frac{dT_i}{dt} = -L_\nu(T_i) - L_\gamma(T_s) + \sum_k H_k$$

- In 10 to 10^2 years heat is transported by electrons into the interior,
  where it is radiated away in νs.
- $T_i \neq T_s$.

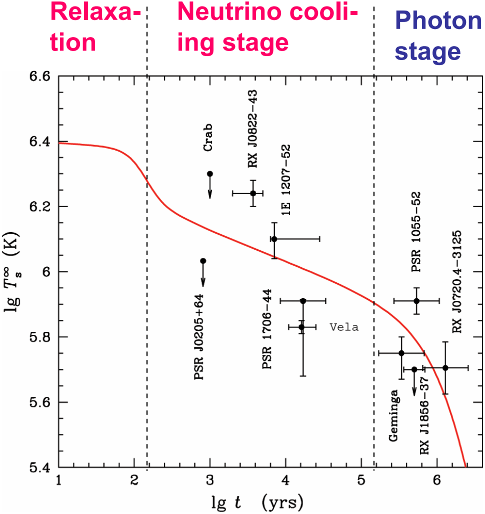
$$\begin{aligned} C_V &= \frac{4\pi}{3}R^3 c_v T_i \\ L_\nu(T_i) &= \int Q_\nu d\mathbf{r} \\ L_\gamma(T_s) &= 4\pi R^2 \sigma T_s^4 \end{aligned}$$

By then the star is in thermal equilibrium.

T_i:=Internal temperature.
T_s:=Surface temperature.
H_k:=Heating mechanisms (frictional heating of superfluid neutrons in the inner crust or exothermal nuclear reactions.)

Q_ν := Neutrino emissivity

Cooling Timescales



Relaxation

Neutrino cooling stage

Photon stage

Red line is model of Modified Urca (slow cooling) by Yakovlev & Pethick (2004)

ν cooling- emissivity

$Q_\nu := \nu$ emissivity

- Depends on specific reactions (microphysics).
- In general two forms are found:

$$\begin{aligned} Q_\nu^1 &= Q_1 T_i^8 \\ Q_\nu^2 &= Q_2 T_i^6 \end{aligned}$$

- From where the ν luminosity is:

$$\begin{aligned} L_\nu^1 &= \frac{4\pi R^3}{3} Q_1 T_i^8 \\ L_\nu^2 &= \frac{4\pi R^3}{3} Q_2 T_i^6 \end{aligned}$$

In the ν - cooling era: $L_\nu << L_\gamma$
Neglect other processes ($H_k \sim 0$).

$$C_V(T_i)\frac{dT_i}{dt} = -L_\nu(T_i) = \begin{cases} \frac{4\pi R^3}{3} Q_1 T_i^8 \\ \frac{4\pi R^3}{3} Q_2 T_i^6 \end{cases}$$

from where we find:

$$T_i \sim \begin{cases} t^{-1/6}, \text{ for } L_\nu^1 \\ t^{-1/4}, \text{ for } L_\nu^2 \end{cases}$$

$L_\nu^1 \Rightarrow$slow cooling.
$L_\nu^2 \Rightarrow$fast cooling.

But how to relate T_s and T_i?

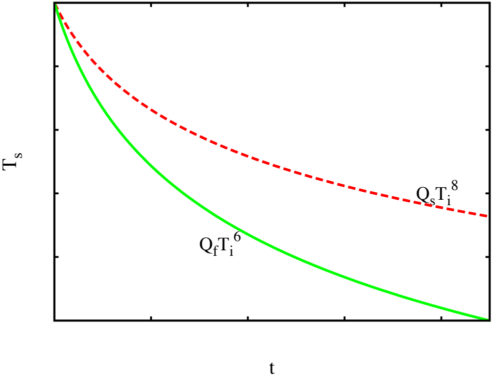
T_i and T_s

Assume a power law:

$$T_s = \kappa_{\text{env}} T_i^{\frac{1}{2}+a}$$

- Here κ_{env} and a depend on the composition of the envelope.
- It has been found $a << 1$ for most of the proposed compositions.
- Then from previous slide:

$$T_s \sim \begin{cases} t^{-1/12}, \text{ for } L_\nu^1 \\ t^{-1/8}, \text{ for } L_\nu^2 \end{cases}$$



ν emission processes

At high densities

Name	Process	Q_ν[erg/cm^{3}s]	L_ν[erg/s]
Dir. Urca	$n \to p + e + \bar{\nu}_e$	$\simeq 10^{27} T_9^6$	$10^{46} T_9^6$
	$p + e \to n + \nu_e$		
Quark Urca	$d \to u + e + \bar{\nu}_e$	$\simeq 10^{26} \alpha_c T_9^6$	$10^{41-42} T_9^6$
	$u + e \to d + \nu_e$		
Kaon Condensate	$n + K^- \to n + e + \bar{\nu}_e$	$\simeq 10^{24} T_9^6$	$10^{42} T_9^6$
	$n + e \to n + K^- + \nu_e$		
Pion condensate	$n + \pi^- \to n + e + \bar{\nu}_e$	$\simeq 10^{26} T_9^6$	$10^{44} T_9^6$
	$n + e \to n + \pi^- + \nu_e$		

At any density

Name	Process	Q_ν[erg/cm^{3}s]	L_ν[erg/s]
Mod. Urca	$n + n' \to n' + p + e + \bar{\nu}_e$	$\simeq 10^{20} T_9^8$	$10^{40} T_9^8$
	$p + e + n' \to n' + n + \nu_e$		
Bremsstrahlung	$N + N \to N + N + \nu_\ell + \bar{\nu}_\ell$	$\simeq 10^{20} T_9^8$	$10^{38} T_9^8$

$$T_n = \frac{T}{10^n \mathrm{K}}$$

Checking the Urcas

Direct Urca

$n \rightarrow p + e + \bar{\nu}_e$

$p + e \rightarrow n + \nu_e$

Effectively:

$n \rightarrow n + \nu_e + \bar{\nu}_e$

Charge Neutrality

Since gravitational attraction should win against Coulomb repulsion:

$$\frac{Ze^2}{R} \leq \frac{G(Am_b)m}{R}$$

Then net charge number:

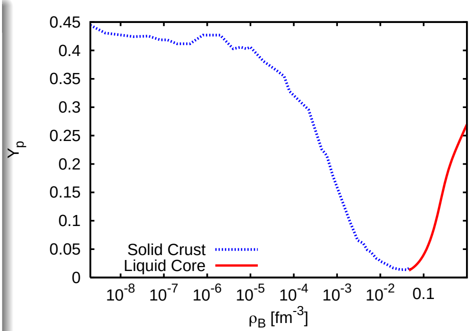
$$Z \leq \begin{cases} 10^{-39}A, & \text{electron added} \\ 10^{-36}A, & \text{proton added} \end{cases}$$

- Composition does not change, $Y_e = \text{const}$.
- $n_p = n_e$ (charge neutrality).
- But if n_p is too small since: $p_p = (3\pi^2 n_p)^{1/3}$ $\Rightarrow$ p_p & p_e, are too small.
- Direct Urca could only occur at high densities.

Conditions for Direct Urca

$n_p = Y_e n_b$ and $n_n = (1 - Y_e) n_b$

- $\Rightarrow$ Can produce neutrons if $p_p + p_e > p_n$
- $p_e + p_p = 2p_p$
  $p_p = (3\pi^2 Y_e n_b)^{1/3}$ and
  $p_n = (3\pi^2 (1 - Y_e) n_b)^{1/3}$
- $Y_e > {}^1/_9$ and $n_e > n_n/8$
- Then Direct Urca is limited to happen at high densities, $n_b > 2n_0$.



Neutron Star Composition

Standard cooling scenario -Slow cooling

- νs from modified Urca:
  $n + N \rightarrow p + N + e + \bar{\nu}_e$
  $p + N + e \rightarrow n + N + \nu_e$
- Extra nucleon is needed to conserve momentum.
- T decreases gradually.
- Assume direct Urca can not happen, then neutron star should be observable for $\sim 10^6$ years.

Accelerated cooling scenario

- νs from direct Urca:
  $n \rightarrow p + e + \bar{\nu}_e$
  $p + e \rightarrow n + \nu_e$
- $\rho_c \sim 10^{15}\text{g}/\text{cm}^3$ or exotic composition.
- $T \simeq 5 \times 10^6$K by 10^2 years. (Sharp drop in T).
- Exotics or high density where $Y_p >^1 /_9$

If $\mathcal{M} > 1.35\mathcal{M}_\odot$, it allows Urca processes.
But $\mathcal{M} < 1.35\mathcal{M}_\odot$, it undergoes standard cooling.

Assuming modified Urca (Standard cooling scenario):

1. ν emission dominates for 10^5y.

$$L_\nu \sim 5.3 \times 10^{39} \frac{\text{erg}}{s} \frac{M}{M_\odot} \left(\frac{\rho_0}{\rho}\right)^{1/3} T_9^8$$

2. Bremsstrahlung from the crust dominates after 10^5y:

$$L_\gamma \sim 5 \times 10^{39} \frac{\text{erg}}{s} \frac{M_{\text{crust}}}{M_\odot} \left(\frac{\rho_0}{\rho}\right)^{1/3} T_9^6$$

3. γ cooling dominates (X-rays)

$$T_n = \frac{T}{10^n\text{K}}$$

$\rho_0 :=$ nuclear saturation density

Pairing

Star is cooling, at some point $T \sim T_c \Rightarrow$ Can form Cooper pairs.

Pairing mechanism

Process	$Q_\nu[\mathrm{erg/cm^3 s}]$
$n + n \to [nn] + \nu + \bar{\nu}$	$\simeq 10^{21} T_9^7$
$p + p \to [pp] + \nu + \bar{\nu}$	$\simeq 10^{19} T_9^7$

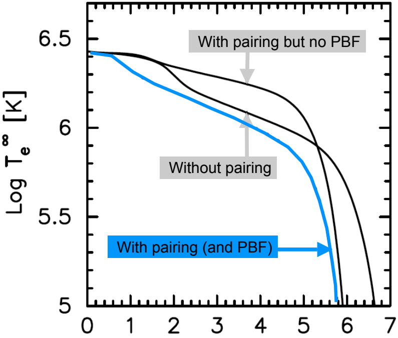
- Note that breaking pairs can make νs too.
- Location of T_c change cooling, e.g. if T_c is large $\Rightarrow$ fast cooling to moderate cooling.
- At some point when T is too low, ν emissions from pairing is suppressed.

Cooling including pairing

- **Cooling scenarios are affected by superfluidity.**
- Once the breaking of pairs starts, L_ν increases.

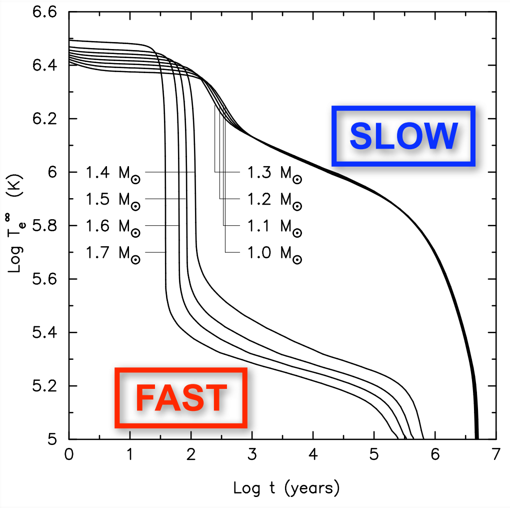
- Excitations of the superfluid: Breaking of Cooper pairs (PBF).
- Does not need K or π condensation.
- Once $T < T_c$ excitations are suppressed by $e^{-\Delta/T}$.

But Δ and T_c are unknowns.



D. Page (2010), Voskresensky, et al. (1986)

Mass and Cooling



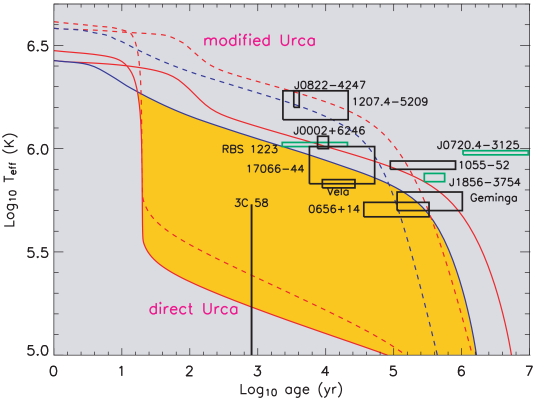
Shape is important, threshold mass is unknown. Direct Urca simulations by Page & Applegate (1992)

Cooling compilation

– Simulations excluding Superfluidity

– Simulations including Superfluidity

– **Direct Urca including Superfluidity**



Lattimer & Prakash (2010)

Urca casino in Rio de Janeiro

Boring!

Cooling and Equation of State

- Cooling depends on C_v and Q_ν, which depend on the structure and composition of the star (on the Equation of State).
- The Equation of State (EoS) is particularly important in the case of middle age stars. These are the neutrino cooling years.
- $Y_p(n_b)$ determined by the nuclear interaction, it is related to Isospin dependence
  $\Rightarrow$ interaction with stronger Isospin dependence could make Y_p higher at lower densities.
- Direct Urca could be possible even if there is not exotic matter
  $\Rightarrow$ (Fast cooling $\neq$ Exotic matter).

Direct Urca and Y_p

A Nuclear Model

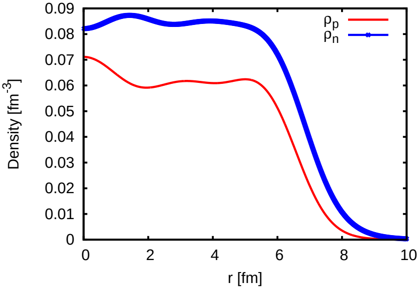
- Consider a nucleon-nucleon interaction.
- Reproduce masses of nuclei (physics at earth densities).
- Reproduce nuclear matter constrains (binding energy at saturation density, etc.)
- Isospin dependence can varies.

Nuclear Matter, $Y_p = \frac{1}{2}$

Sat. Density	n_0	$0.148\ \mathrm{fm}^{-3}$
Binding Energy	$\frac{E}{A}(n_0)$	-16.3 MeV
Compressibility	K	271.7 MeV
Effective Mass	$\frac{M^*}{M}(n_0)$	0.60

Neutron Skin: $\delta R = R_n - R_p$

^{208}Pb



Density distributions

- Nuclei with more neutrons than protons ($Y_p < 1/2$) have a δR.
- Different Nuclear models (and parametrizations) predict different δR $\Rightarrow$ δR depends on the Isospin dependence.

Construct an EoS for neutron-rich matter

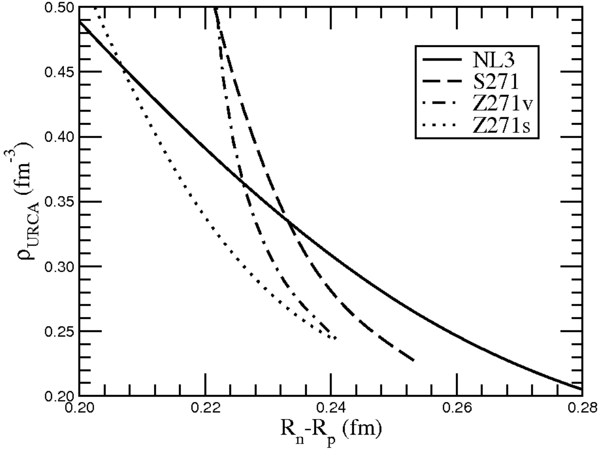
For neutron stars at $n_b > n_0$:

- $n \leftrightarrow p + e^- + \bar{\nu}_e \quad \Longleftrightarrow \quad \mu_n = \mu_n + \mu_e$
- $e^- \leftrightarrow \mu^- + \nu_e + \bar{\nu}_\mu \quad \Longleftrightarrow \quad \mu_e = \mu_\mu$
- Charge neutrality $\Longleftrightarrow$ $n_p = n_e + n_\mu$
- Direct Urca condition $\Longleftrightarrow$ $p_p + p_e \geq p_n$.

Threshold density for D. Urca, n_{URCA}, defined by:

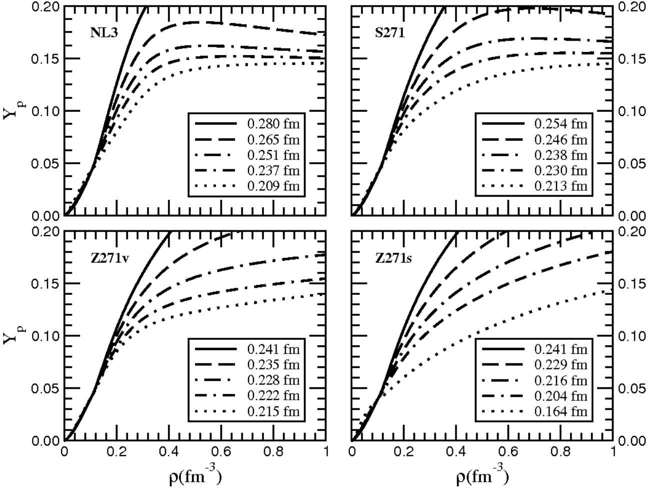
$$p_p + p_e = p_n$$

URCA critical density and δR of ^{208}Pb



Using RMF, Horowitz and Piekarewicz, PRC **66**,055803 (2002)

Composition after saturation density



Using RMF, Horowitz and Piekarewicz, PRC **66**,055803 (2002)

- Correlation between the interaction, the δR, and n_{URCA}:

$$\begin{aligned} \delta R &\gtrsim 0.25\ \mathrm{fm} \quad \Rightarrow \text{D. Urca is likely.} \\ \delta R &\lesssim 0.2\ \mathrm{fm} \quad \Rightarrow \text{D. Urca is unlikely.} \end{aligned}$$

- The larger the neutron skin, the lowest the threshold density for direct Urca.
- Parity Radius Experiment (PREX) at Jeferson Lab: elastic $e+{}^{208}\mathrm{Pb}$ scattering aimed to measure δR can constrain the isospin dependence of the nuclear interaction.
- Note that this process is a electroweak process (γ and Z^0 exchange) $\Rightarrow$ nuclear model independent.
- Then the extrapolation to Neutron-Rich matter could be reliable.

P-REX

Then how does N.S.s cool?

- Until now all cooling models can reproduce the observations.
- Superfluidity is important to understand cooling processes.
- Envelope composition is assumed to be dominated either by heavy elements or by light elements (unknown really). ⇒ No narrow spectral lines are observed.
- If assume a heavy elements atmosphere, fits well for stars older than 10^5yr.
- If assume a light elements atmosphere, fits well for stars younger than 10^5yr.
- For very massive neutron stars, accelerated cooling is favoured (No conclusive).
- New observations of extremely hot and extremely cold neutron stars are needed.
- Currently, can not constrain more EoSs from cooling observations due to uncertainties on T and age.
- If from PREX D. Urca cooling is ruled out, then observations of enhanced cooling (fast cooling) would imply the existence of exotic states of matter at the core of neutron stars.

NS. vs. Manhatan

Wondering about dinner?

Coming soon...

- Pairing in nuclear matter (Wim).
- Dispersive Optical Model (Seth).
- EoS and TOV equations (Me).
- Colour superconductivity and exotic matter in Neutron Stars (Simin).
- Pulsars, glitches, and gravitational waves from Neutron Starts (Kai).

References

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